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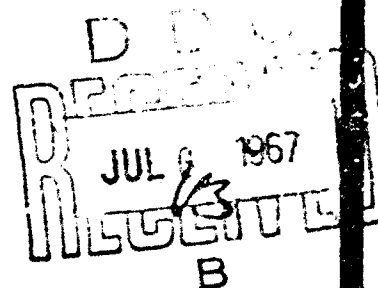
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A review of some recent progress in understanding catastrophic yaw

by J. D. Nicolaides

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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

A REVIEW OF SOME RECENT PROGRESS IN
UNDERSTANDING CATASTROPHIC YAW

by

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SUMMARY

Catastrophic Yaw and Roll Lock-In are studied at supersonic and subsonic speeds. Roll Lock-In is found to occur on isolated fins and is traced to a leading edge vortex. Free rolling motions are found to be accurately represented by the Roll Lock-In Theory. Catastrophic Yaw is observed in three-degree-of-freedom and six-degree-of-freedom wind tunnel tests. Mass asymmetry in a 10° cone is found to cause rolling velocity, Roll Lock-In, and Catastrophic Yaw.

RESUME

Les questions du lacet catastrophique et du mouvement de roulis dont la fréquence est la même que le mouvement de nutation ("roll lock-in") sont étudiées en supersonique et en subsonique. On a constaté que ce dernier mouvement se produit sur des ailettes isolées et qu'il est dû aux tourbillons qui prennent naissance au bord d'attaque de l'ailette. La théorie concernant le "roll lock-in" se révèle représenter avec précision les mouvements de roulis libres. Des essais en soufflerie à trois et à six degrés de liberté ont permis de constater le phénomène du lacet catastrophique. On trouve qu'une asymétrie de masse dans un cône d'angle au sommet de 10° donne lieu à la vitesse de roulis, au "roll lock-in" et au lacet catastrophique.

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A REVIEW OF SOME RECENT PROGRESS IN UNDERSTANDING CATASTROPHIC YAW

John D. Nicolaides

1. INTRODUCTION

The most important problem facing the exterior ballistician today is Catastrophic Yaw.^{1, 2} The designers of bombs, finned projectiles, re-entry missiles, and unguided rockets must all overcome this problem. History, both recent and past, records numerous failures in all fields. What is clearly needed is a better understanding of Catastrophic Yaw, and Roll Lock-In, which is the necessary condition for Catastrophic Yaw.

Roll-Yaw Resonance in fin-stabilized free-flight missiles has been known for many years. The linear theory (i.e. Tricyclic Theory)³ has been successfully used, both to predict the motion of missiles when the various stability coefficients were known, and to determine the various stability coefficients when the actual motion was known.

The Tricyclic Theory yields the complex angle of attack as

$$\vec{\alpha} = K_N e^{(\lambda_N + i\omega_N)t} + K_P e^{(\lambda_P + i\omega_P)t} + K_T e^{i\omega t} \quad (1)$$

When

- $\vec{\alpha}$ = $\beta + i\delta$
- K_N = nutation arm
- K_P = precession arm
- K_T = trim due to configurational, mass, or thrust asymmetries
- $\lambda_{N,P}$ = damping rates
- $\omega_{N,P}$ = rotation rates
- p = rolling velocity of missile

While there have been many examples of the excellence of the Linear Tricyclic Theory, there have been an ever increasing number of cases where the linear theory simply does not work. In these cases two special features stand out. First, the missile's rolling motion stays the same as the frequency of the wobbling motion; and, second, the size of wobbling motion is much larger than predicted by the linear theory. This special rolling motion is called Roll Lock-In and this special large wobbling motion is called Catastrophic Yaw^{1, 2}.

In this case of Catastrophic Yaw, Equation (1) reduces to either

$$\vec{\alpha} = (K_N e^{\lambda_N t} + K_T) e^{i\omega_N t}, \text{ when } p = \omega_N = \text{constant}, \quad (2)$$

or
$$\vec{\alpha} = K_T e^{i p t}, \text{ where } p \neq \omega_N. \quad (3)$$

In both cases the roll angle of the missile with respect to the plane of the complex angle of attack is a constant (Roll Trim Angle) and the wobbling motion is, thus, Lunar.

It has been found that Roll Lock-In is caused by the action of the Induced Roll Moment. It has, also, been found that Catastrophic Yaw is due to the Roll Lock-In which produces a Roll Trim Angle which, in turn, causes an Induced Side Moment. This Side Moment during Roll Lock-In acts like a Magnus moment so as to reduce the damping of the nutational or precessional components. The size of the Trim component at resonance is greatly increased, therefore, due to this Side Moment.

A better understanding of Catastrophic Yaw could come about if we had a better understanding of the Induced Roll Moment causing Catastrophic Yaw.

2. ROLL LOCK-IN

At the University of Notre Dame we have been studying the causes and nature of Roll Lock-In at both subsonic and supersonic speeds^{4, 5}.

In the subsonic case, it was known that Roll Lock-In could exist. So our interests were primarily concerned with the flow conditions which cause Roll Lock-In. Some preliminary studies were carried out by using the Smoke Wind Tunnel.

In the supersonic case, it was not known whether Roll Lock-In could occur. Thus, we sought to find Roll Lock-In and to study its characteristics.

2.1 Subsonic Roll Lock-In

In previous studies it was found that Roll Lock-In occurred on free-rolling cruciform fins by themselves.⁶ It had originally been thought that vortices shedding off the body of the missile caused Roll Lock-In. The flow around the body of the Low Drag Bomb was studied by Professor Brown. Figure 1 shows the body vortices at 53° angle of attack. The periodic shedding may be noted. These same flow features are seen at smaller angles of attack. It was also noted that small asymmetries at the bomb's nose could significantly affect the flow field. However, by testing cruciform fins by themselves, the same Roll Lock-In characteristics were obtained.

Thus, in the Notre Dame subsonic tests, the cruciform fins from the Low Drag Bomb were used by themselves in studying the flow field.

It was noted in the flow studies that strong vortices were originating directly behind the leading edge of the fins. Figure 2 shows this vortex on a flat plate which is at an angle of attack of 90° and is rotating. The vortex is seen on the retreating fin.

This same vortex is seen on a free-rotating cruciform fin system when a particular fin has a certain combination of angle of attack and angle of side step (i.e. a particular roll orientation, γ_T).

In the case of Roll Lock-In, this fin leading edge vortex is quite prominent. Our studies suggest that it is this vortex that produces the Induced Roll Moment which overcomes the Roll Moment due to cant and, then, produces Roll Lock-In.

$$L(\delta_A) + L(\gamma_u \alpha) = 0 \quad (4)$$

or

$$\gamma_T = \frac{C_{l_{\delta_A}} \delta_A}{C_{l_{\gamma_u \alpha}} \alpha} \quad (5)$$

Special tests have been carried out at Notre Dame studying various configurational changes. Of particular importance is the work of Mr Daniels of the Naval Weapons Laboratory.

2.2 Supersonic Roll Lock-In^{5, 7, 4}

Supersonic Roll Lock-In studies have been carried out on three configurations, the Aerobee Rocket, the Basic Finner, and the Aerobee Fins (Figs. 3 and 4). Their rolling motions are shown in Figures 5-8.

The Roll Lock-In Theory is given by

$$\gamma = \gamma_T + B e^{\lambda t} \cos(\omega t + \delta) \quad (6)$$

where

$$\gamma_T = \text{Roll Trim Angle (Equation (5))}$$

$$\lambda = \frac{1}{2I_x} \left(C_{l_p} \frac{d}{2v} \frac{1}{2} \rho v^2 s d \right)$$

$$\omega = - \frac{1}{I_x} (\bar{C}_{l_{\gamma_u \alpha}} \frac{1}{2} \rho v^2 s d) \quad .$$

This Roll Lock-In Theory has been "fitted" to these rolling motions by using a special technique developed by Professor Eikenberry which employs the Method of Differential Corrections. The results are given in Tables I-III.

The Roll Lock-In Theory has been found to represent the rolling motion to an accuracy of less than 2°.

Also, it has been found possible to determine quite accurate values for the Roll Trim Angle, the Induced Roll Moment Stability Coefficient, and the Roll Damping Moment Stability Coefficient.

2.3 Exceptions and Modification to the Theory

Not all of the experimental rolling motions, however, have been represented by the Theory. Figures 9 and 10 illustrate some interesting exceptions. In Figure 9 the Roll Trim Angle is changing slowly with time. In Figure 10 the missile is seeking three different Roll Trim Angles, 90° apart. This "hunting" characteristic may be due to poor wind tunnel flow or it may be real. Some of our studies suggest that it is real and it is due to poor roll dynamic stability and to serious non-linearities.

It was also observed that (i) differences in fin area and (ii) mass asymmetries affected the rolling motion. Thus a Modified Roll Lock-In Theory has been developed;

$$L(\delta_A) + L(p) + L(\gamma_u \alpha) + L(\gamma, \alpha) + L(\Omega m) = I_x \dot{p}.$$

For the wind tunnel case where α is a constant and the transient rolling motion has damped ($\dot{p} = p = 0$), we may solve for the new Roll Trim Angle. Here we find that the model will, in fact, prefer one fin orientation to the other three. Special model designs and tests should be carried out to study this motion and its dynamic stability.

3. WIND TUNNEL CATASTROPHIC YAW TESTS

The complete three-degrees-of-freedom angular motion of two missiles has been studied in special wind tunnel tests.

The first missile was the Basic Finner. By mounting a model on a unique central pivot, the model was able to freely pitch and yaw. The fore and aft portions of the model were able to freely roll due to the angle of cant on the fins. By carefully selecting the angle of cant, this model was able to demonstrate Catastrophic Yaw. Movies were taken and are shown. The films are now being measured and the motion is being studied.

Also, a second model of a 10° cone was free-flight tested in the University's Vertical Free Flight Wind Tunnel and in the Air Force Vertical Wind Tunnel at Wright Field. The six-degree-of-freedom motions were observed. Roll Lock-In and Catastrophic Yaw were obtained. The data is being analyzed. A special film of these motions was shown for the first time at the Conference.

When the cone model had no mass asymmetry, there was no rolling velocity, and the pitching and yawing motions were quite well damped. However, when mass asymmetry was introduced a large rolling velocity was created. Also, a large and persistent circular and lunar pitching and yawing motion existed. This motion is accurately represented by Equations (2) and (3).

4. CONCLUSIONS

It is concluded that

- (i) Roll Lock-In exists at both subsonic and supersonic speeds.
- (ii) The cruciform fins, not the body of the missile, are the origin of Roll Lock-In.

- (iii) Vortices originating at the fin leading edge cause Roll Lock-In.
- (iv) Missile fin area and mass asymmetries can cause preferential Roll Trim Angles.
- (v) Catastrophic Yaw may be demonstrated in a wind tunnel (a) by using a special three-degree-of-freedom pivot (b) by free flight tests in a vertical stream.
- (vi) Mass asymmetries in a simple 10° cone model cause a rolling velocity, Roll Lock-In, Lunar motion, and Catastrophic Yaw.

REFERENCES

1. Nicolaides, John D., *Two Non-Linear Problems in the Flight Dynamics of Modern Ballistic Missiles*. IAS Report No. 59-17, 1959.
2. Nicolaides, John D., *Missile Flight and Astrodynamics*. TN 100A, Bureau of Naval Weapons, 1961.
3. Nicolaides, John D., *On the Free Flight Motion of Missiles Having Slight Configurations Asymmetries*, Ballistics Research Laboratories Report No. 858, 1953, and IAS Preprint No. 395, 1952.
4. Nicolaides, John D., Eikenberry, Robert S., *Dynamic Wind Tunnel Testing Techniques*, AIAA Paper No. 66-752, 1966.
5. Nicolaides, John D., Stumpfl, Stephen C., *On Roll Lock-In In Unguided Rockets*, UNDAS-TR-668JDN, SCS, August 1966, under Contract NSR-15-004-016 prepared for NASA, Washington, DC.
6. Griffin, T.F., Heald, R., *On the Pure Rolling Motion of the Low Drag Bomb at Large and Small Angles of Attack*, Department of the Navy, Ballistic Technical Note No. 79, Washington, DC.
7. Bozzonetti, E.R. Jr., *Analysis of the Oscillatory Motions Associated with Roll Lock-In*. Report, Department of Aero-Space Engineering, University of Notre Dame, 1966.

TABLE I

Basic Finner Constants from Computer Fit

γ_T	S_T	B	λ	ω	δ
(deg)	(deg/sec)	<u>Damping Mode</u>		(rad/sec)	(rad)
37.1	-0.416	(deg)	(sec ⁻¹)	4.25	3.78
P.E. 0.255	0.047	17.5	-0.135	0.0071	0.026
		0.482	0.0073		
		<u>Undamping Mode</u>			
49.3	2.08	26.2	0.023	3.86	4.73
P.E. 0.507	0.240	0.693	0.0115	0.0113	0.024

TABLE II

Basic Finner Aerodynamic Data

<i>Damping</i>			<i>Undamping</i>	
	<i>Value</i>	<i>% Error</i>	<i>Value</i>	<i>% Error</i>
γ_T	37.1°	0.687	49.3°	1.029
Cl_{γ_α}	-0.027	0.1646	-0.019	0.285
Cl_p	-6.66	0.518	1.11	47.8

TABLE III
Aerobee "Fins Only"

<i>Parameter</i>	<i>Value</i>	<i>Probable Error</i>
γ_T	43.784 ⁰	0.507 ⁰
S_T	-8.361 ⁰	3.335 ⁰
λ	3.212	0.492
ω	130.717	0.468
B	6.409	0.578
δ	4.244	0.086
Sum of residuals squared	364.0	
Probable error of fit	1.875 ⁰	

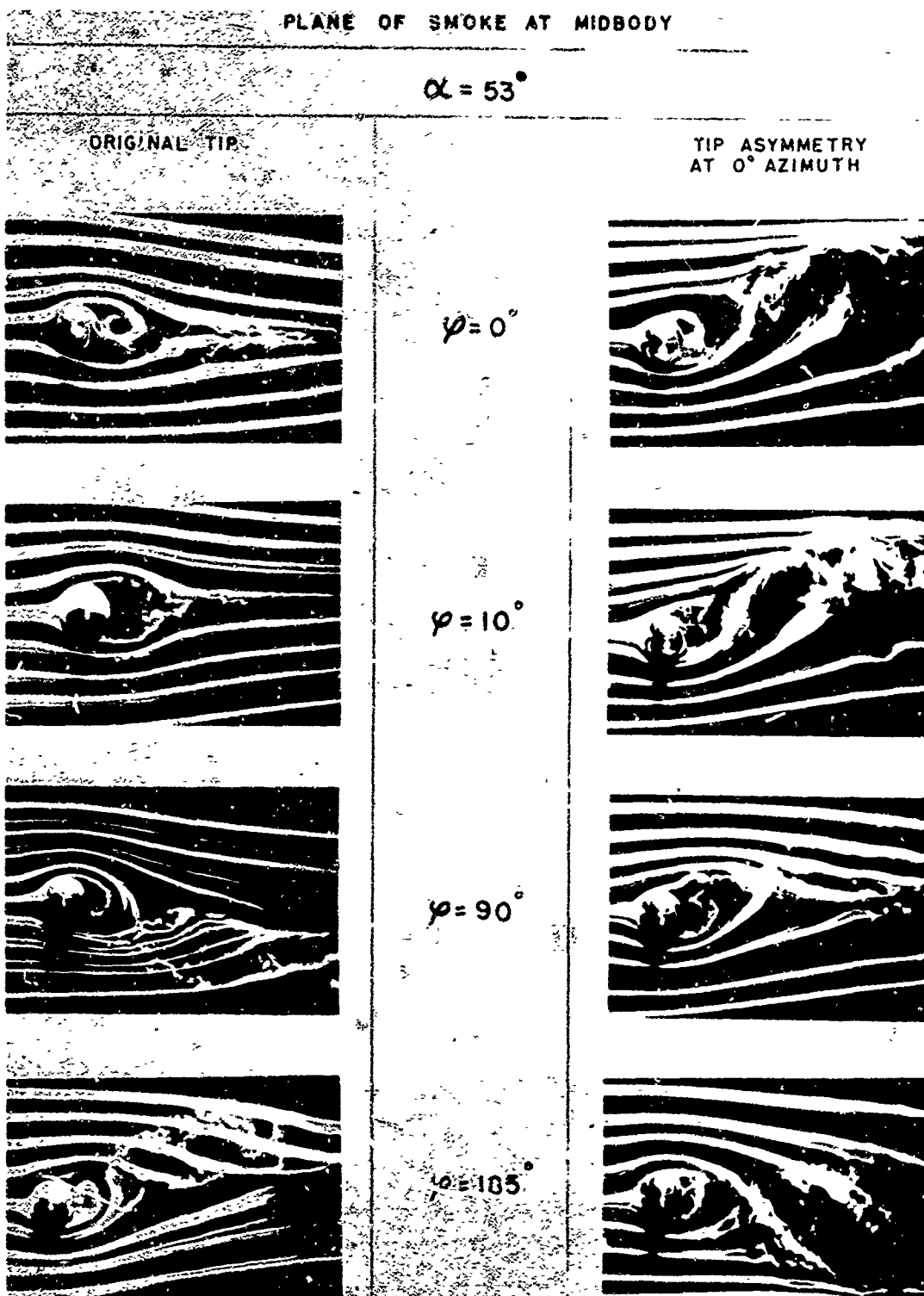


Fig. 1 The effects of slight rotational asymmetry of the model tip on the variation with roll of the vortex configuration



Fig.2 Vortex on a rotating flat plate

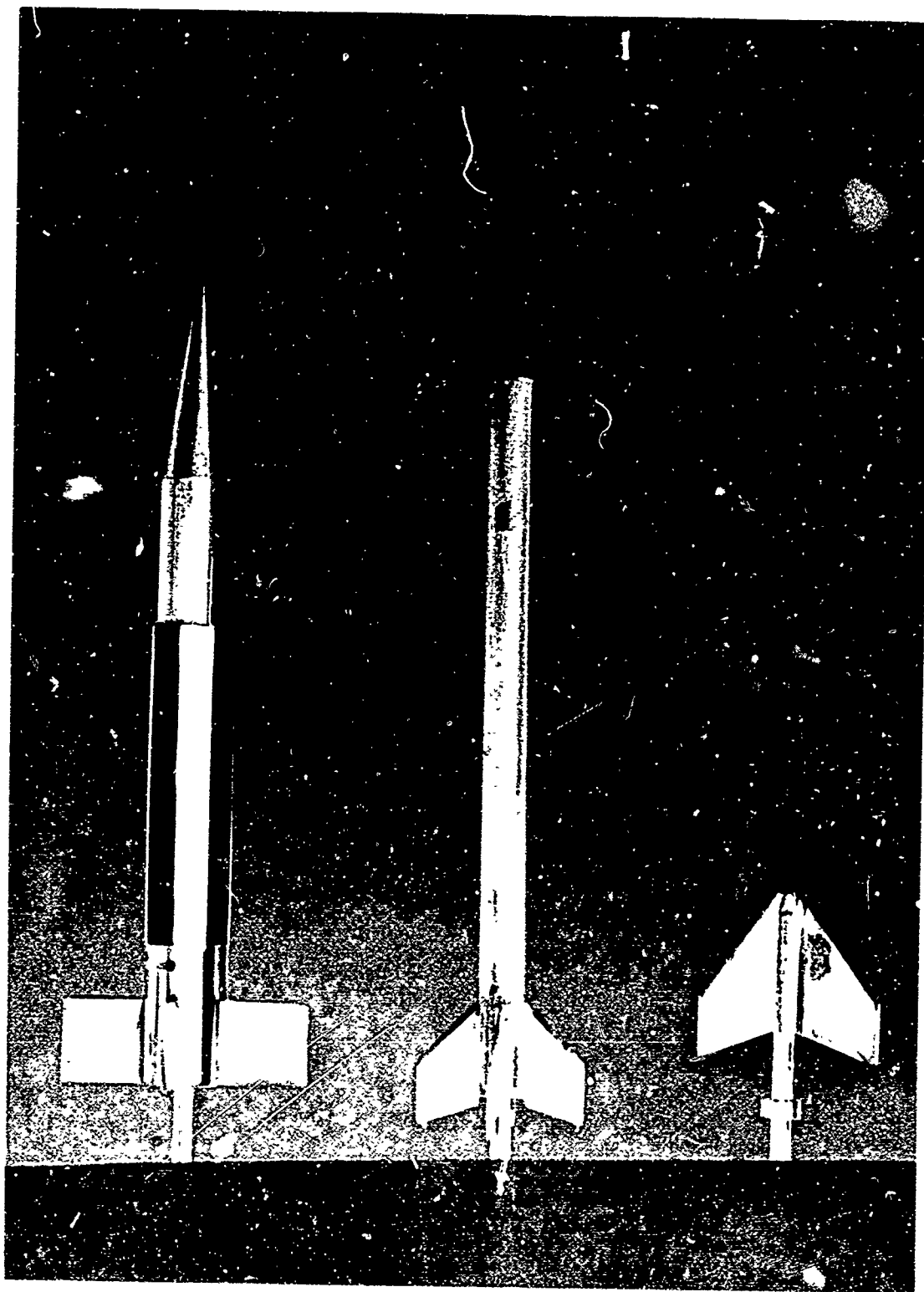


Fig.3 The three configurations studied for supersonic roll lock-in

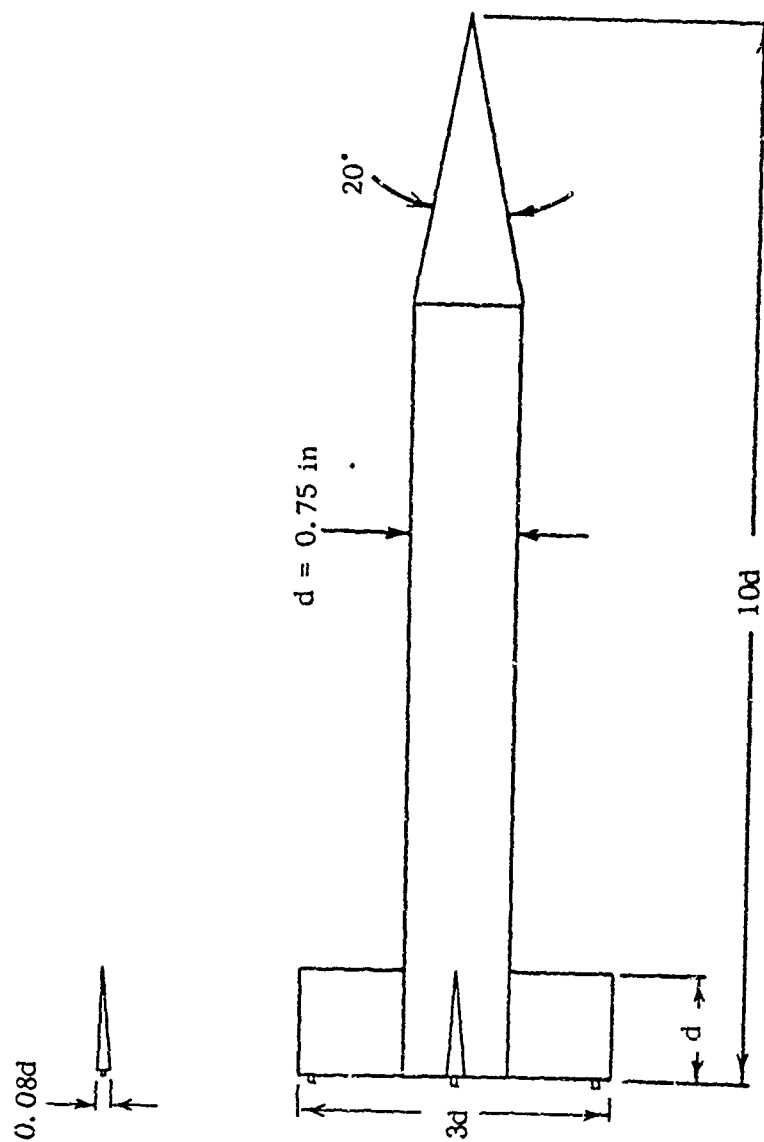
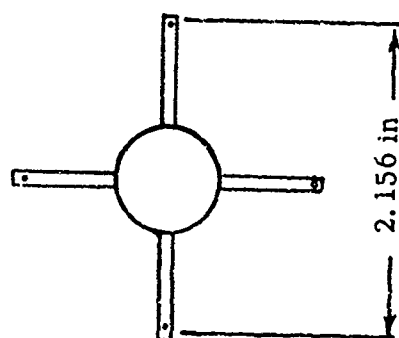


Fig. 4 Basic finner model



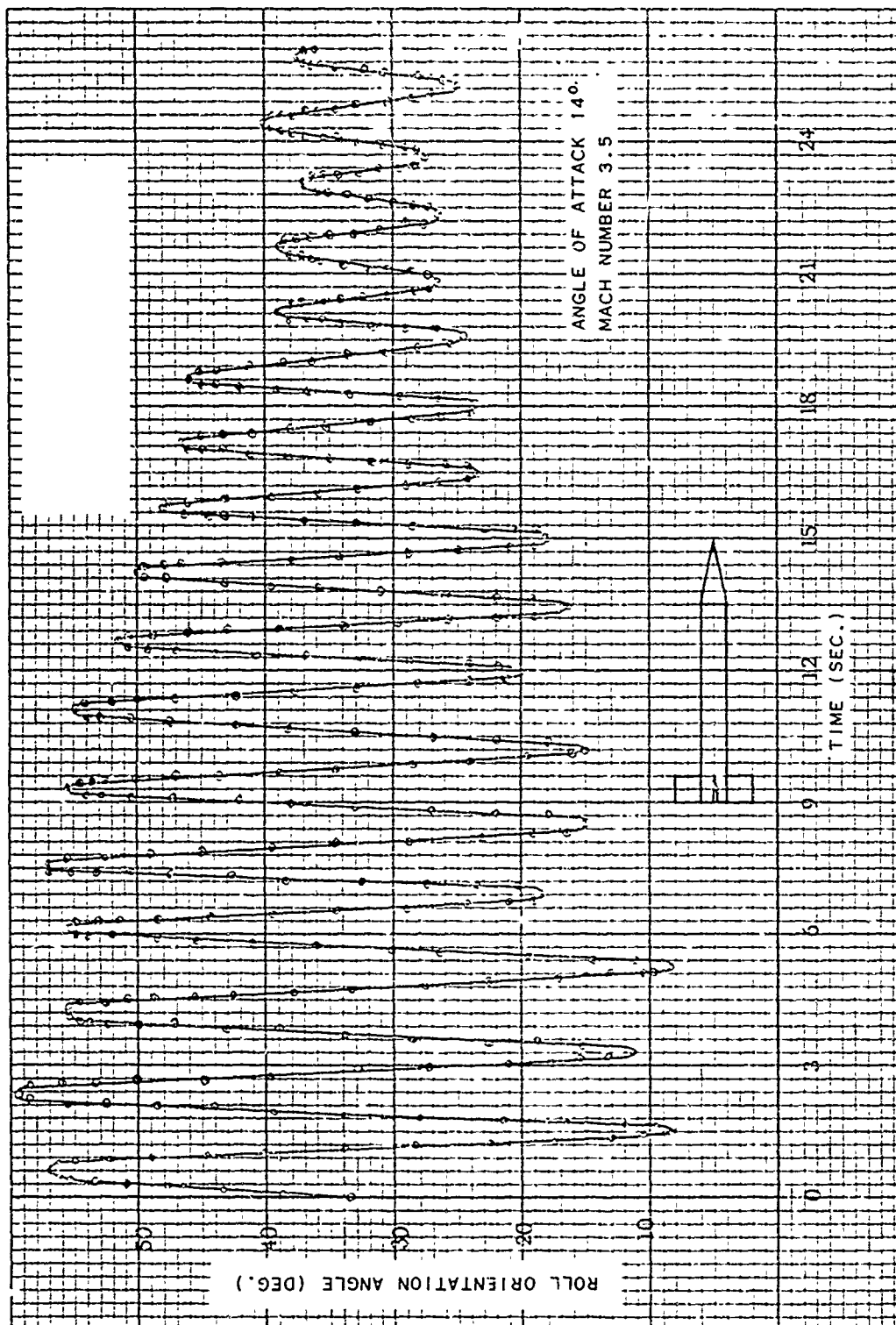


Fig. 5 Roll lock-in basic finner missile

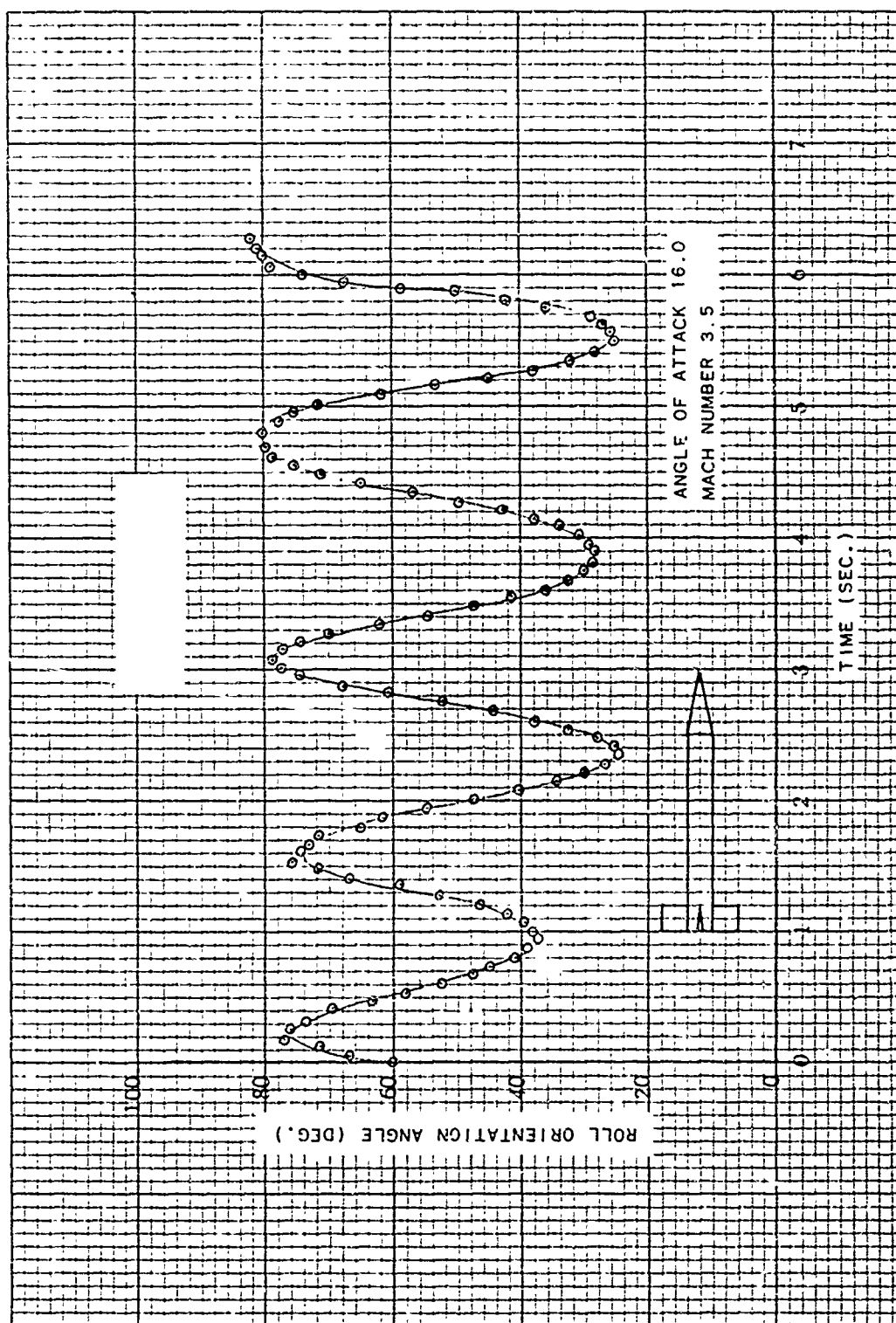


Fig. 6 Roll lock-in

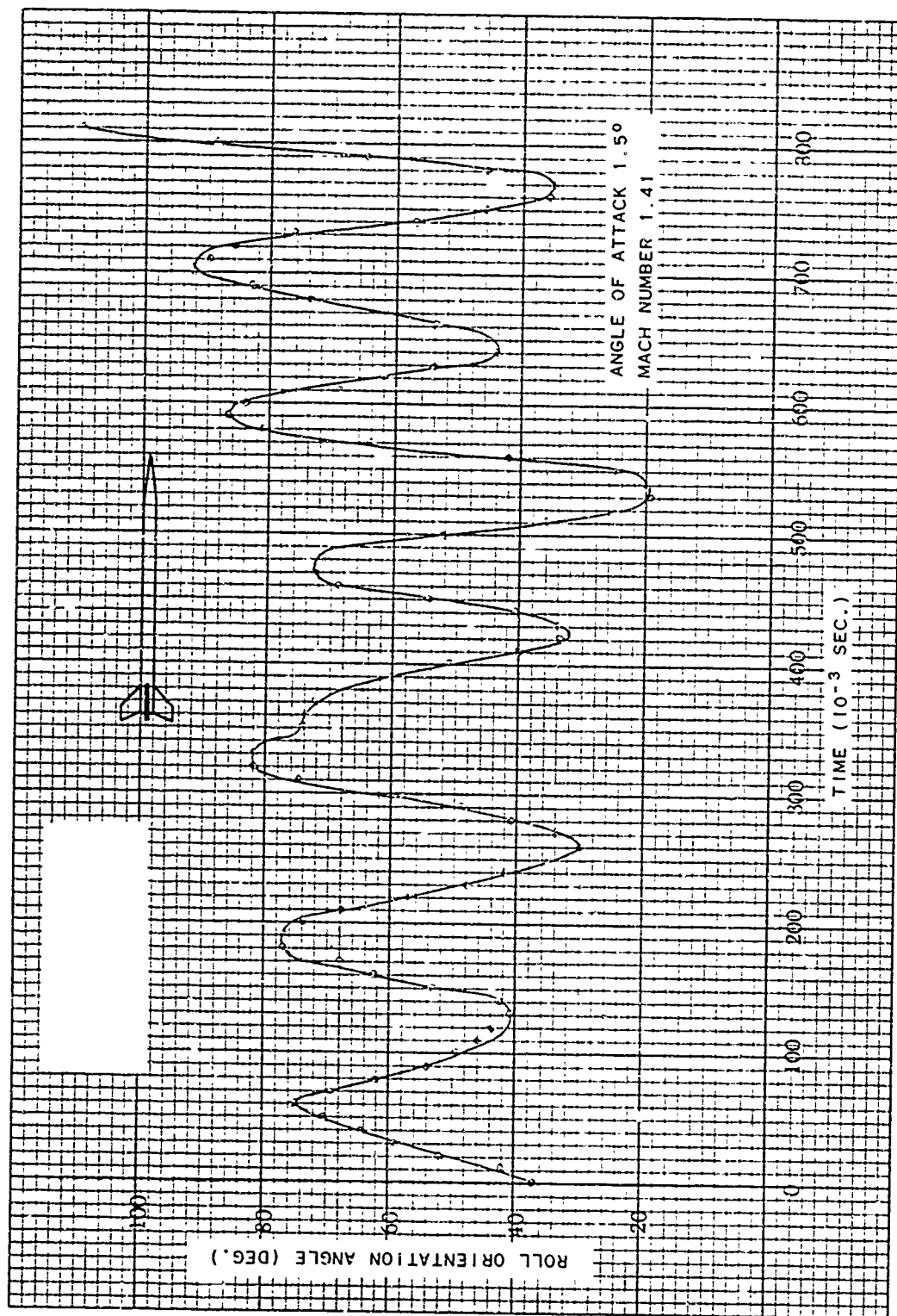


Fig. 7 Roll lock-in Aerobee 350

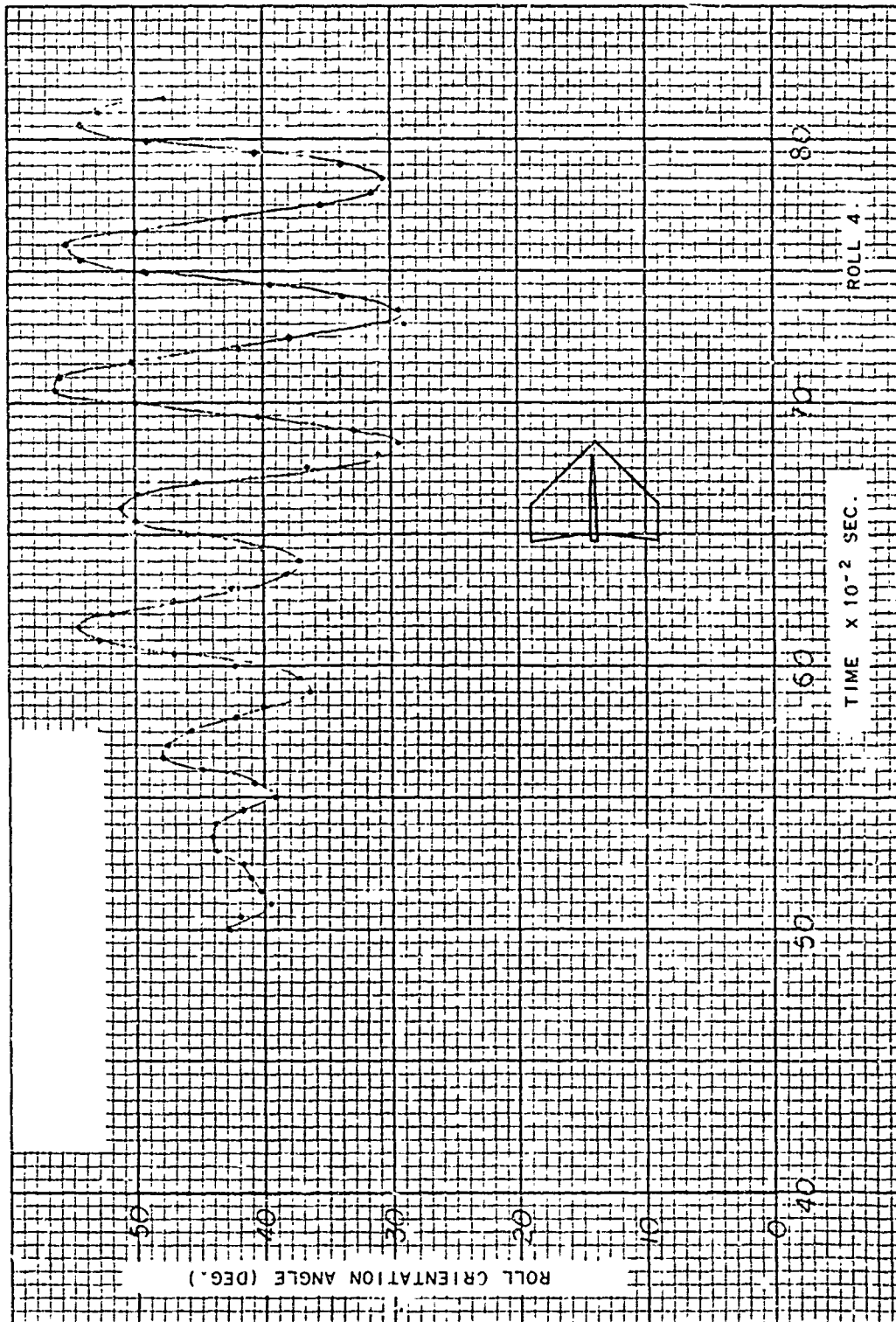


Fig. 8 Induced mode "undamping" motion

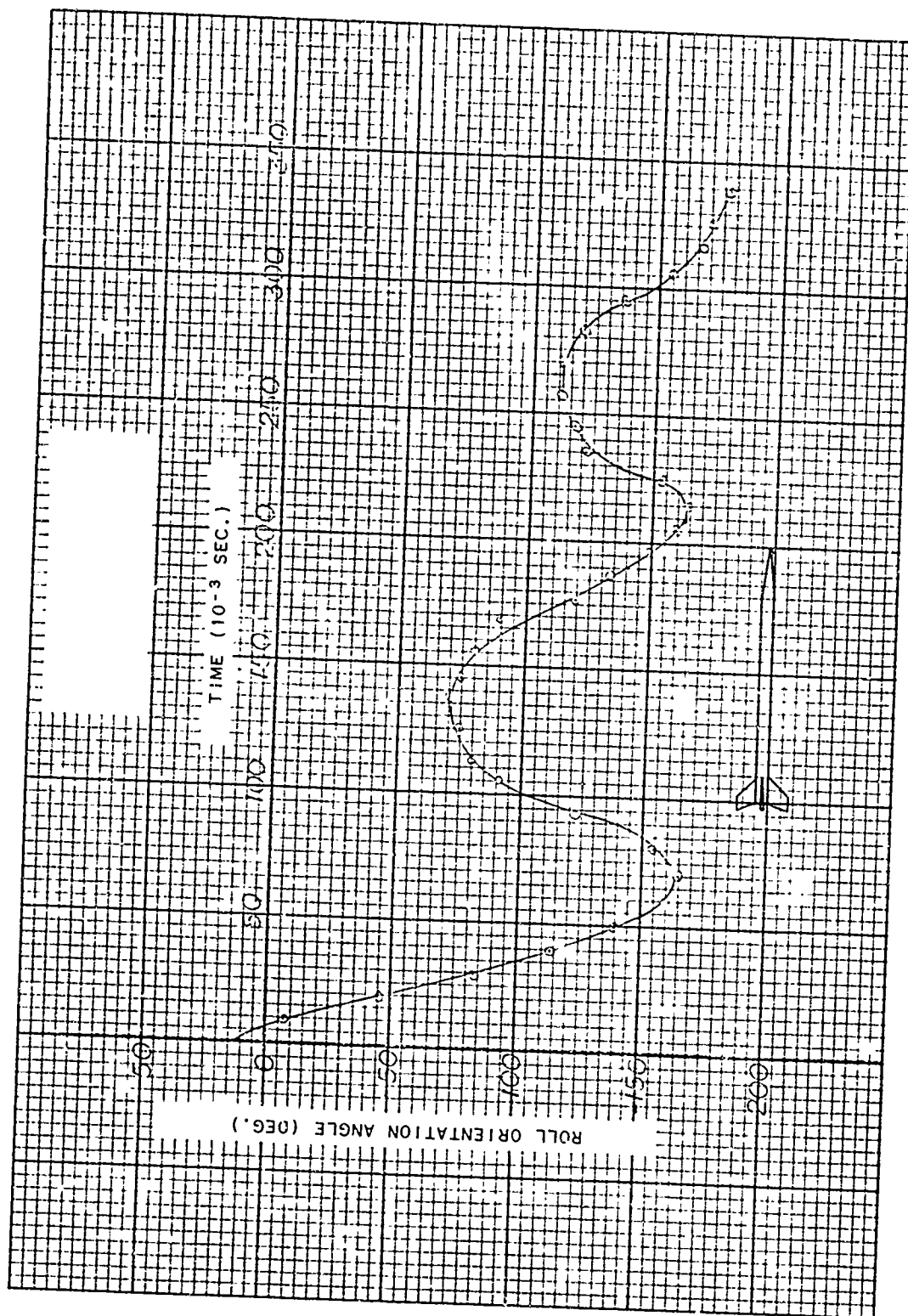


Fig. 9 Roll lock-in Aerobee 350

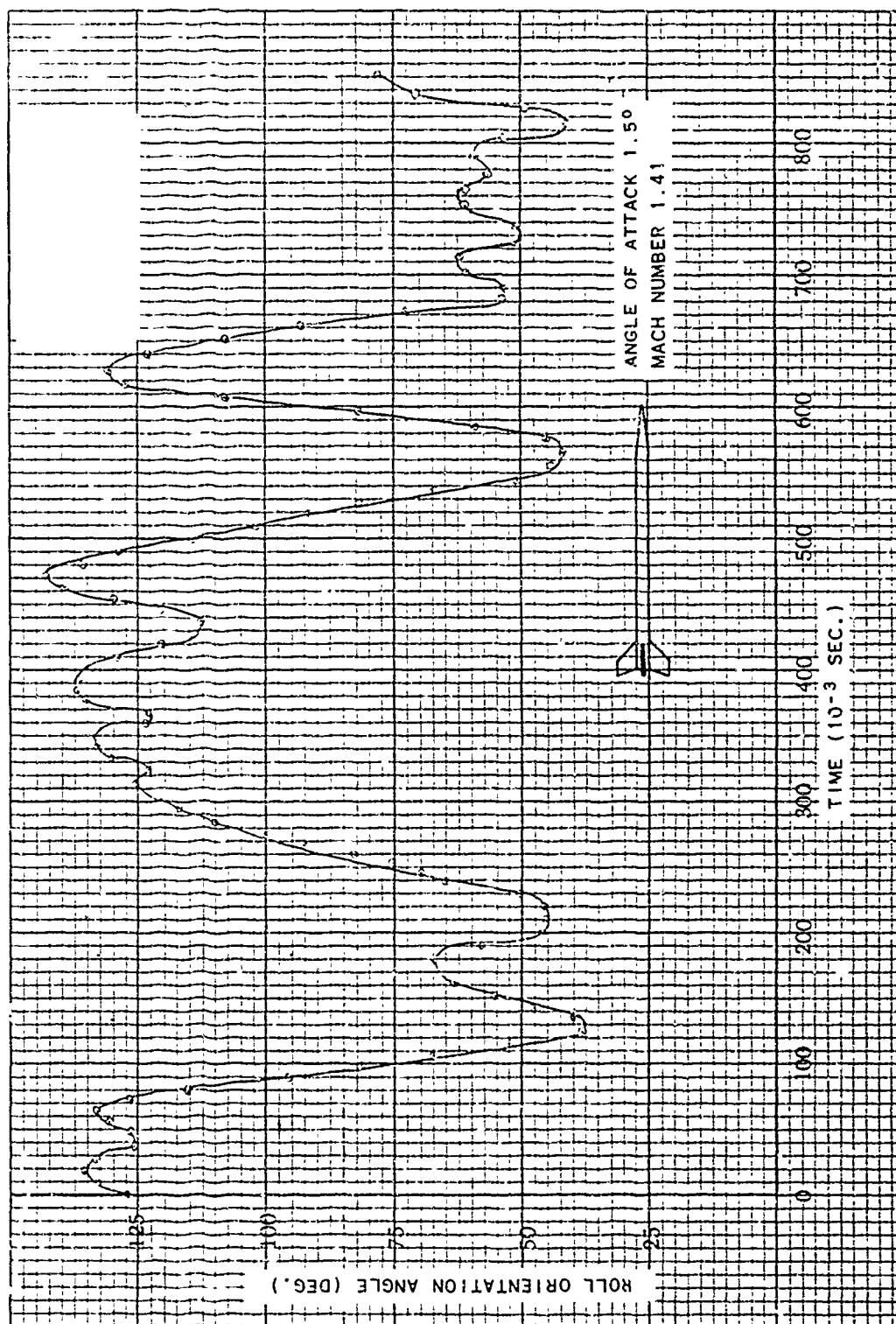


Fig.10 Roll lock-in Aerobee 350

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